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Division V

LOADING TESTS OF THE EMBEDDED ANCHORAGE USING ULTRA-HIGH-PERFORMANCE-CONCRETE

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ABSTRACT

The application of ultra-high-performance-concrete (UHPC), used in skyscraper, to the anchorage part of nuclear power plants is expected to improve structure performance. In this study, the basic characteristics tests were conducted for anchorage embedded in the concrete plate and the one embedded in shear wall, both test specimens were casted in use of UHPC. As a result, it was confirmed that the anchorage strength of UHPC can be evaluated by design formula of Japan Electric Association Code JEAC4601-2015 (JEAC) (Japan Electric Association 2015). In addition, evaluation method to improve the strength by the effect of steel fiber was proposed.

INTRODUCTION

In order to further improve the safety of nuclear power plants, the new regulatory requirements in Japan are based on not only the conventional seismic loads but also the loads of external hazards such as tsunami and tornadoes. In particular, extremely thick walls are necessary for exterior walls. The application of ultra-high-performance-concrete (UHPC), used in skyscraper, to the anchorage part of nuclear power plants is expected to improve structure performance.

In Japan, the anchorage part of piping and equipment embedded in concrete shear wall is designed in accordance with the Japan Electric Association Code JEAC4601-2015 (JEAC) (Japan Electric Association 2015) and Design Recommendations for Composite Constructions (AIJ 2010) which were developed based on various tests (Pull-out test, shear test, etc.) conducted in the past. However, these design guidelines are applicable to normal concrete of Fc60 or less, and there are few studies (Sakai et al. 2006, Ishilawa et al. 2016) on anchorage using UHPC.

In this study, the basic characteristics tests were conducted for the anchorage part embedded in the concrete plate and the one embedded in shear wall. Both test specimens were casted using UHPC. From the test results, the anchorage design was proposed based on the formula in JEAC.

In this study, the following two kinds of tests were conducted.

・Basic characteristics tests of embedded anchorage

・Tests of shear wall embedded anchorage

This study had been carried out in the project "Development of technical infrastructure for upgrading materials, structures and construction methods of nuclear power plant buildings".

BASIC CHARACTERISTICS TESTS OF EMBEDDED ANCHORAGE

In the basic characteristics tests of embedded anchorage, loading tests were conducted for the UHPC test specimen with a single anchor and embedded anchors in order to confirm the pulling, shear and bending behaviour.

Test Specimen

Figure 1 shows the single anchor test specimen, Figure 2 shows the test specimen of the embedded anchors, and Photo 1 shows the test specimen. The concrete materials of the test specimens were UHPC containing steel fiber (1% mix ratio) with design strength of 150 N/mm2 (Fc150) and UHPC with design strength of 100 N/mm2 (Fc 100). The concrete compressive strength of each test specimen is shown in Table 1.

The size of the test specimen was determined by referring to the general embedded anchors of the actual plant. High strength bolts (strength category 12.9), which are relatively easy to obtain, were used for the anchor bolts so that concrete could be damaged rather than bolts. The tensile strength of the stud after welding was 90 kN for φ 16 and 164 kN for φ 22. The tensile strength of the high strength bolt was 1203 N/mm^2 and the yield strength was 1262 N/mm^2 from the result of the material tensile test.

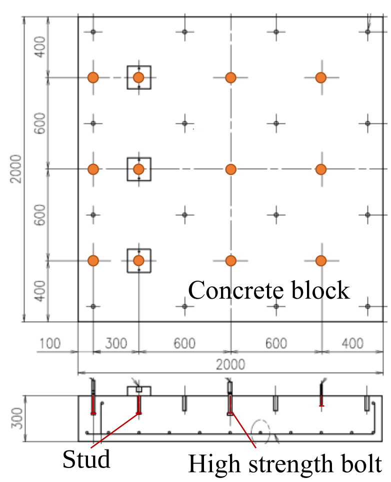


Figure 1. Single anchor test specimen

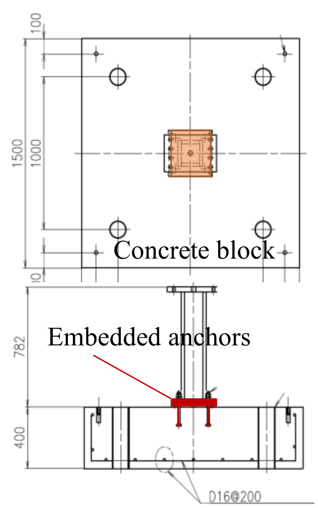
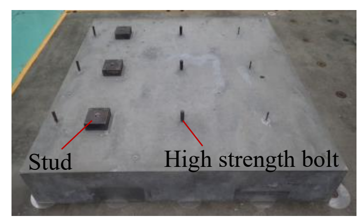
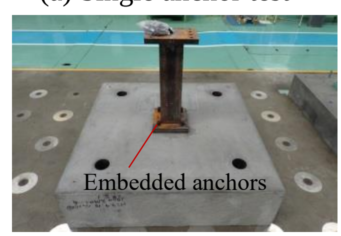


Figure 2. Embedded anchors test specimen



(a) Single anchor test



(b) Embedded anchors test

Photo 1. Test specimen

Table 1: Concrete strength of test specimens*1

Single anchor test specimen	Concrete compressive strength (N/mm^2)	Embedded anchors test specimen	Concrete compressive strength (N/mm^2)
Fc100	122.1	Fc100	122.3
Fc150*2	155.0/159.8	Fc150*2	166.1/166.3

*1 Test results of concrete test pieces whose age is almost the same as the test specimen.
*2 For the Fc150 test specimen, the strength of 2 test pieces casted on different date is shown.

Test Parameter

Table 2 shows the single anchor test cases, and Table 3 shows the embedded anchors test cases. Based on the concept of specimen selection listed on Table 2, the parameters of the single anchor test were concrete design strength, anchor type, anchor shape, and load conditions. A total of 14 cases (3 specimens per case) were tested. Assuming the anchorage part of actual plant, the parameter of the embedded anchors test were concrete design strength, anchor type, and load conditions. A total of 4 cases were tested.

Table 2: Single anchor test case

Test case	Concrete	Concept of test specimen selection	Anchor bolt	Loading condition
B1-1	Fc100	General studs were selected from anchorage part of actual piping	Stud φ16 L120	Pull-out
B1-2	Fc150			
B2-1	Fc100	Same shape as B1 and assume concrete fracture	High strength bolt φ16, L120	
B2-2	Fc150			
B3-1	Fc100	Check the effect of bolt diameter on fracture mode	High strength bolt, φ22, L120	
B3-2	Fc150			
B4-1	Fc100	Check the effect of embedding length on fracture mode	High strength bolt φ16, L100	
B4-2	Fc150			
B5-1	Fc100	Check the effect of stud diameter and embedding length on fracture mode	Stud φ22, L80	
B5-2	Fc150			
B6-1	Fc100	1/2 scale of the actual bolt diameter	High strength bolt φ8, L60	
B6-2	Fc150			
B7-1	Fc100	Assume concrete fracture due to shear load	High strength bolt φ16, L120	Shear
B7-2	Fc150			

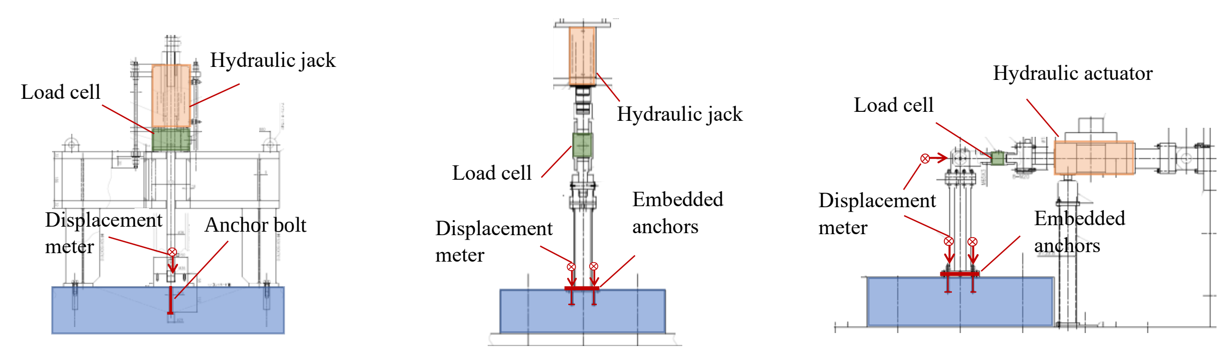
Table 3: Embedded anchors test case

Test case	Concrete	Concept of test specimen selection	Anchor bolt	Loading condition
E-A	Fc100	Model the actual piping The embedded anchors of high strength bolts are used on the assumption of concrete fracture.	High strength bolt φ16, L120	Pull-put
E-B	Fc150			
E-C	Fc100			Cyclic bending
E-D	Fc150	Model the embedded anchors of actual piping	Stud φ16, L120	

Test Method

Figure 3 shows the outline of the test apparatus for the single anchor pull-out test, the embedded anchors pull-out test, and the embedded anchors cyclic bending test.

In the single anchor test, quasi-static pull-out loading or shear loading was applied using a hydraulic jack, and the loading was applied until the anchor or concrete was damaged. In the embedded anchors pull-out test, as in the single anchor test, the loading was applied using a hydraulic jack until damage occurred. In the embedded anchors cyclic bending test, cyclic loads were incrementally loaded using a hydraulic actuator in a quasi-static manner, and the loading was applied until damage occurred. In each test, the load of the hydraulic jack or actuator and the displacement of the anchor bolt were measured.



(a) Single anchor pull-out test (b) Embedded anchors pull-out test (c) Embedded anchors cyclic bending test

Figure 3. Overview of test apparatus

Test Results

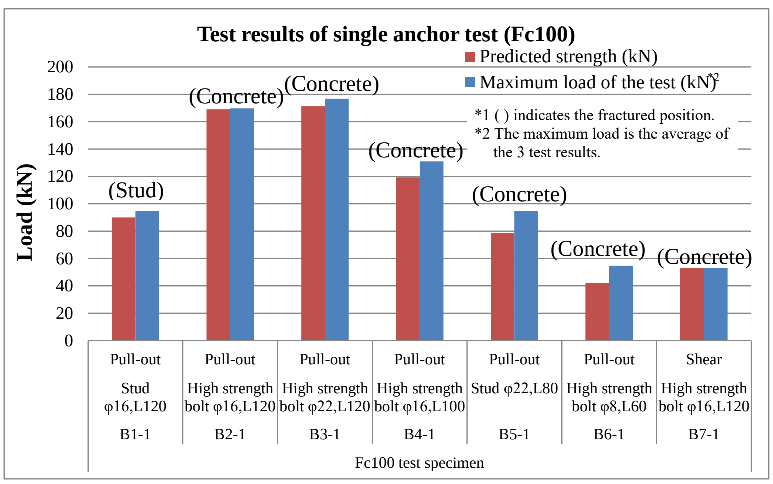
Figure 4 shows the test results of the single anchor test. The predicted strength is the strength calculated based on the anchor design formula. The design formula of predicted strength of concrete corn failure Pc and predicted ultimate strength of stud/bolt failure Ps are shown below.

$$Pc = Ac \times 0.31\sqrt{Fc} \tag{1}$$
$$Ps = As \times \sigma_B \tag{2}$$

where Ac is the concrete cone area, As is cross-sectional area of the stud/bolt, Fc is the actual compressive strength of the concrete, and σ_B is the actual tensile strength of the stud/bolt.

The test results were equivalent to or greater than the predicted strength and approximately the same as the estimated results. However, the strength of case B3-2, B4-2 and B7-2 greatly exceeded the predicted strength. This is considered to be owing to the effect of steel fiber mixed in concrete. The strength of the test results of these cases was about 1.8 times greater than the predicted strength.

As an example, a photograph of the case B 3-2 after the test is shown in Photo 2. Photo 2(a) shows the concrete after the test and Photo 2(b) shows the concrete attached to the anchor after the anchor was pulled out. Steel fiber was also observed on the fracture surface of concrete. The concrete cone failure behavior of UHPC in this test was similar to that of normal concrete (Nagasawa et al. 2009).



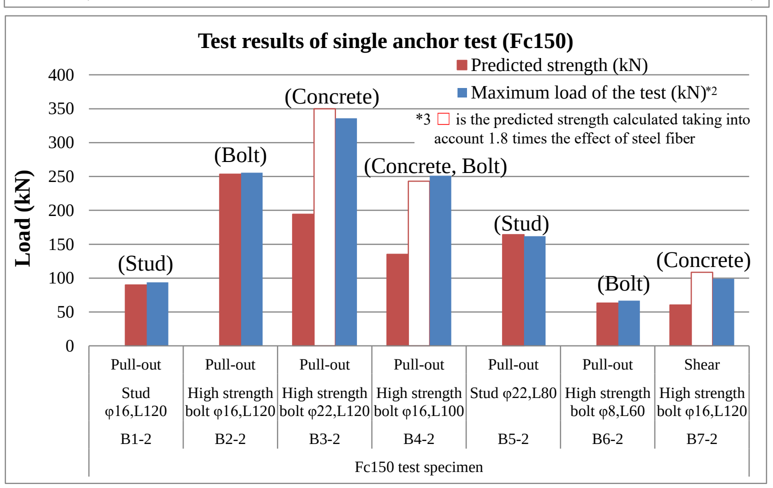
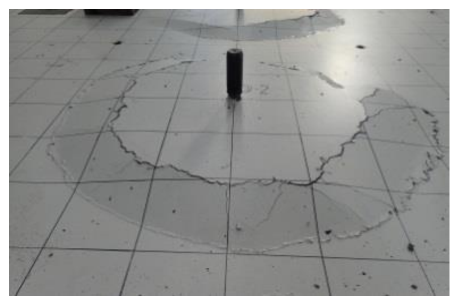
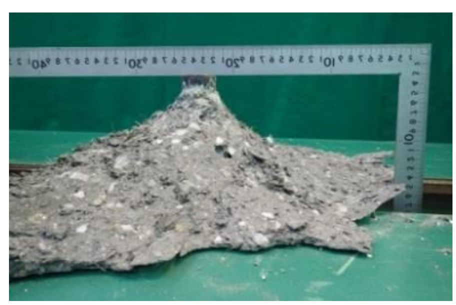


Figure 4. Test results of single anchor test



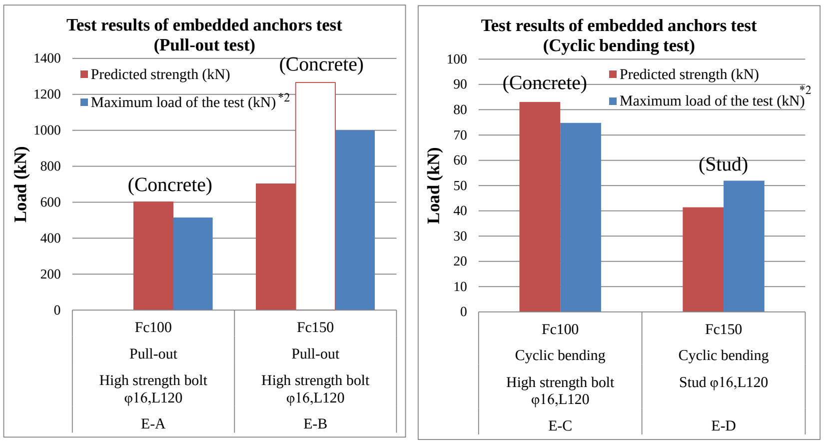
(a) Fracture mode of concrete



(b) Concrete cone failure

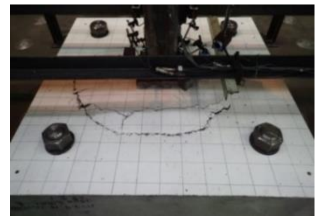
Photo 2. Case B 3-2 (Pull-out, Fc150) test specimen after the test

Figure 5 shows the results of the embedded anchors test. In the embedded anchors pull-out test, the concrete was fractured, and the maximum load was smaller than the predicted strength. In the embedded anchors cyclic bending test, the concrete was fractured in the case E-C and the stud was damaged in the case E-D. As an example, Photo 3 shows the damage of the test specimen after the test for cases E-B (pull-out test) and case E-C (cyclic bending test). In the embedded anchors test, the fracture mode was concrete cone failure, and all cases were damaged in the predicted fracture mode.



*1 ( ) indicates the fractured position. *2 The maximum load is the average of the 3 test results.
*3 □ is the predicted strength calculated taking into account 1.8 times the effect of steel fiber

Figure 5. Test results of embedded anchors test



Case E-B (Pull-out, Fc150)

Case E-C (Cyclic bending, Fc100)

Photo 3. Test specimen after the tests

Comparison with Literature Results

Figure 6 shows comparison between the test results of this study and literature results (Ishikawa et al. 2016). Figure 6 shows the value obtained by dividing the pull-out strength by the cone area taking concrete strength as a parameter. The strength of Fc 100 test specimens was about 0.8 ~ 1.4 times greater than the concrete cone failure predicted strength. The strength of Fc 150 test specimens was about 1.4 ~ 2.0 times greater due to the effect of steel fiber. The strength of the embedded anchors test results was smaller than the single anchor test results due to the group effect of the anchor bolt. This tendency was similar to that of existing normal concrete (Ishikawa et al. 2016) . Comparing the JEAC design formula with the results of this test, the anchor strength of test results was greater than that of the design formula. Therefore, by using the existing design formula of JEAC, the strength of the anchorage part using UHPC can be evaluated on the safe side.

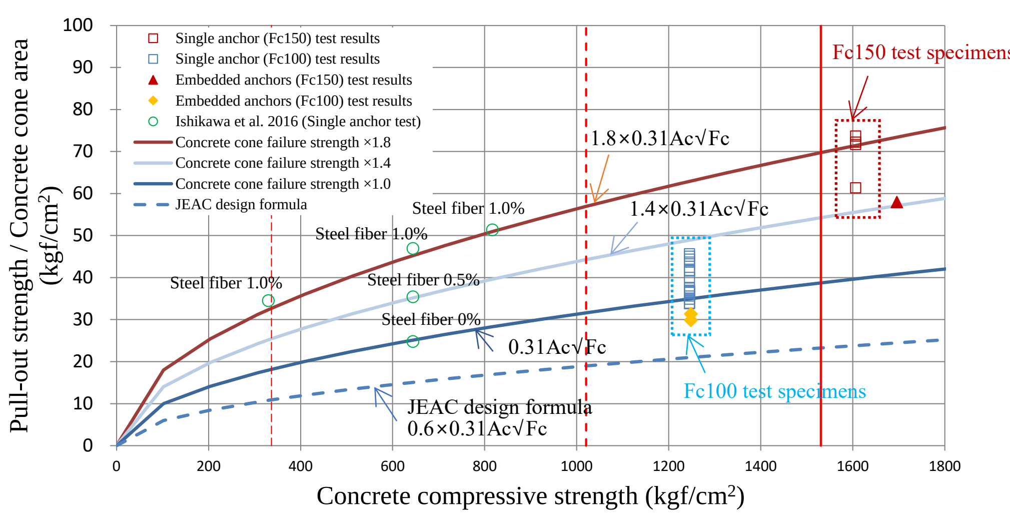


Figure 6. Comparison between the test results of this study and literature results

Summary of Basic Characteristics Tests of Embedded Anchorage

As a result of the basic characteristics tests of embedded anchorage, measured ultimate strength of anchorage using UHPC was confirmed to be greater than the JEAC anchorage strength formula of concrete cone failure, the design formula of JEAC evaluates anchor strength on the safe side. It was also confirmed that the effect of steel fiber improved the anchor strength by at least 1.4 times.

TESTS OF SHEAR WALL EMBEDDED ANCHORAGE

In order to confirm the ultimate pull-out strength focusing on the support function of the anchorage part, the test was carried out in which three embedded anchors in the shear wall were pulled in the out-of-plane direction while applying shear force to the shear wall of UHPC.

Test Specimen

Figure 7 shows the shape and photograph of test specimens. The size of the embedded anchors attached to the test specimen was determined so that the embedded anchors could be attached to both wall surfaces, referring to the embedded anchors normally used in the actual plant and the one in the previous study. Furthermore, since an out-of-plane load was applied to the embedded anchors while shear load was applied to the wall, the test specimen was made by installing the embedded anchors on both sides of the wall for self-balancing. In addition, by arranging the embedded anchors in three rows horizontally with increased pitch, the risk of overlapping the fracture region was reduced.

Test Parameter

Table 4 shows the test cases. The predicted strength *Pu* in Table 4 is the minimum value among the strength of concrete cone failure Ps (equation 1) and the ultimate strength Pc (equation 2) of the stud.

There are parameters of concrete type, anchor type, anchor load, shape, and loading pattern. In this study, basic conditions were set and tests were conducted. The concrete materials of the test specimens were UHPC containing steel fiber (mixing rate 1%) with design strength 150 N/mm2 (Fc150) and UHPC with design strength 100 N/mm2 (Fc 100), and 2 test specimens of the wall were prepared. The type of anchor was stud of diameter φ8 and embedding depth L60mm assuming 1/2 model of typical actual anchorage part. Here, high strength bolts were adopted to the anchor in two cases of test specimen so that concrete cone fracture would occur.

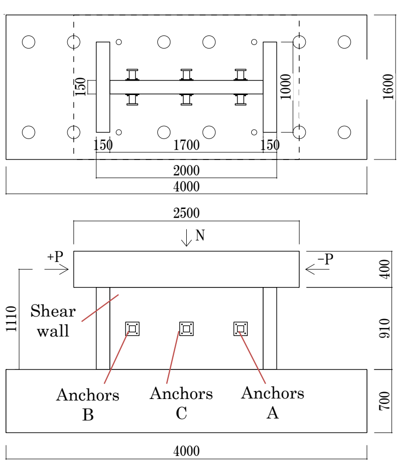


Figure 7. Shape of test specimen

Table 4: Test cases

Test Case	Concrete	Embedded anchors	Anchor type	Shear strain of the wall (Figure 9)	Expected fracture mode	Predicted strength *Pu**3
Fc100 -A	Fc100*1	A	High strength bolt φ8	1000μ	Concrete	157kN
Fc100 -B		B	Stud φ8	2000μ	Stud	97kN
Fc100 -C		C	High strength bolt φ8	ultimate strain	Concrete	157kN
Fc150 -A	Fc150*2	A	High strength bolt φ13	1000μ	Concrete	174kN
Fc150 -B		B	Stud φ8	2000μ	Stud	97kN
Fc150 -C		C	High strength bolt φ13	ultimate strain	Concrete	174kN

*1 The result of concrete compressive strength test of Fc100 was 132N/mm^2
*2 The result of concrete compressive strength test of Fc150 was 163N/mm^2
*3 The predicted strength Pu was calculated using the material tensile test result of the reinforcing bar and the compressive strength test result of the concrete.

Test Method

In order to reproduce the actual behaviour, the test was carried out in which embedded anchors in the shear wall were pulled in the out-of-plane direction while applying shear force to the shear wall. Thus, the pull-out strength focusing on the support function of the anchorage part was confirmed. Figure 8 shows the test apparatus. Figure 9 shows the loading pattern.

The out-of-plane pull-out loading increased in proportion to the shear strain of the wall. Referring to the literature (Suwa et al. 2013), the load was increased using the following equation for the relationship between shear strain and out-of plane pull-out loading.

$$P/Pu = 0.45/2000 \times \gamma_W \tag{3}$$

where P is the out-of-plane pull-out loading, Pu is the predicted strength, and γ_W is the shear strain of the wall.

Since there was a possibility that the cone fracture surfaces of hardware A and hardware C overlapped, the loading procedure was to damage anchors B, C, and A in this order. The shear loading for the wall and the pull-out loading for the embedded anchors were interlocked. First, after the anchors A was pulled up to P/Pu = 0.6 under the condition that the shear strain of the wall was 1000 μ, the pull-out loading of the anchors A was unloaded. Then, after the anchors B was pulled out and damaged at a wall shear strain of 2000 μ, the anchors C was pulled out until it was fractured by interlocking loading. Finally, anchors A was pulled out and damaged under the condition that the shear strain of the wall was 1000 μ.

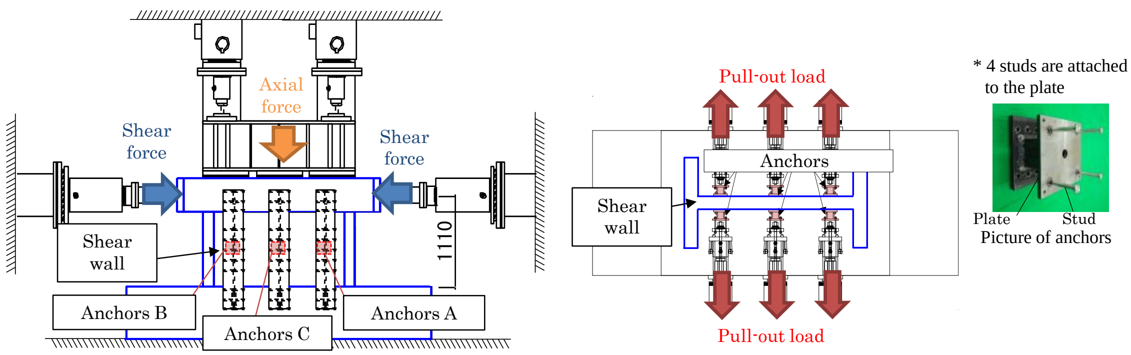


Figure 8. Test apparatus

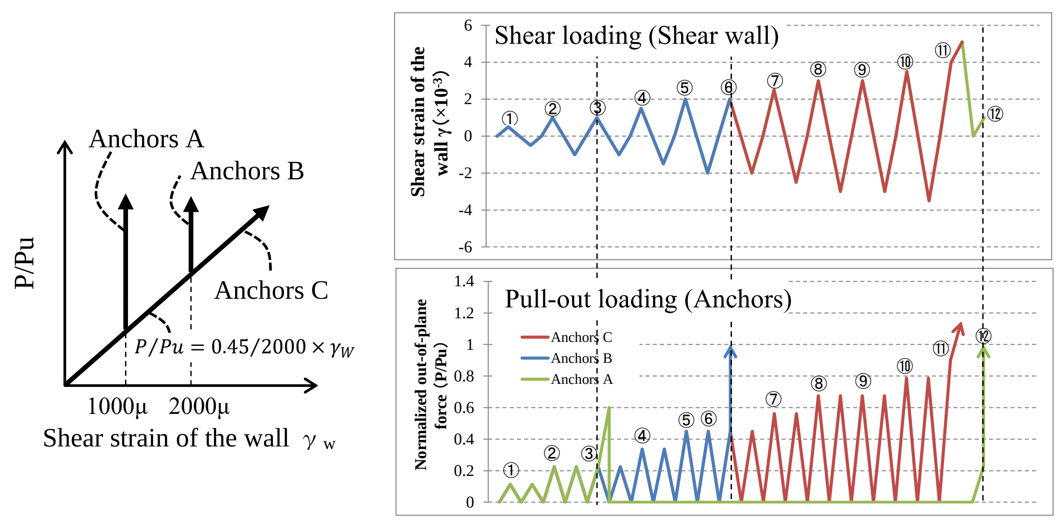


Figure 9. Loading pattern

Test Results

Table 5 summarizes the test results. Based on these results, the relationship between in-plane shear strain of the shear wall and the normalized out-of-plane force of the embedded anchors (*P/Pu*) were summarized and shown in Figure 10. Photo 4 shows the shear wall after anchors C was pulled out.

As shown in Figure 10, any embedded anchors exceeded the criteria of the in-plane shear strain and the normalized out-of-plane force prescribed by JEAC. The fracture mode of anchors A and C were the concrete cone failure. From the test result of Fc 150 test specimen (containing steel fiber), it was confirmed that the result greatly exceeded the JEAC criteria due to the effect of steel fiber.

As a reference, after the test, a pull-out test was carried out on anchors A and C under the condition without applying the shear force to the wall. As a result, P/Pu was about 1.0 ~ 2.5, and it was confirmed that there was sufficient support function of the anchorage part in spite of receiving large shear strain and history of pull-out load.

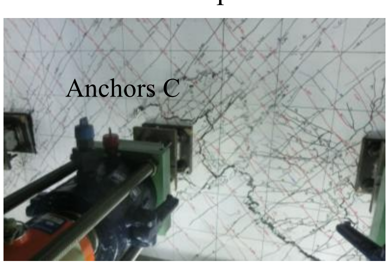
For both Fc 100 and Fc 150 specimens, the anchors B studs were damaged near the predicted stud strength (97 kN), and the results were as predicted

Table 5: Summary of the test results

Test case	Anchors	Fracture mode	Shear strain of the wall γ	Maximum pull-out strength Pu	Normalized out-of plane force *P/Pu*
Fc100-A	A	Concrete	1053μ	160 kN	1.02
Fc100-B	B	Stud	2027μ	93 kN	-[*1]
Fc100-C	C	Concrete	3020μ	105 kN	0.67
Fc150-A	A	Concrete	1016μ	415 kN	2.39
Fc150-B	B	Stud	2020μ	97 kN	-[*1]
Fc150-C	C	Concrete	5137μ	195 kN	1.12
Fc100-A (Reference[*2])	A	Concrete	197μ	160 kN	1.02
Fc100-C (Reference[*2])	C	Concrete	199μ	175 kN	1.11
Fc150-A (Reference[*2])	A	Concrete	401μ	441 kN	2.53
Fc150-C (Reference[*2])	C	Concrete	449μ	246 kN	1.41

*1 Since the stud of anchors B were damaged rather than concrete, *P/Pu* was not calculated.
*2 As a reference, after the test, a pull-out test was carried out under the condition without applying the shear force to the wall.

Fc 100 test specimen



Fc 150 test specimen

Photo 4. The shear wall after anchors C was pulled out

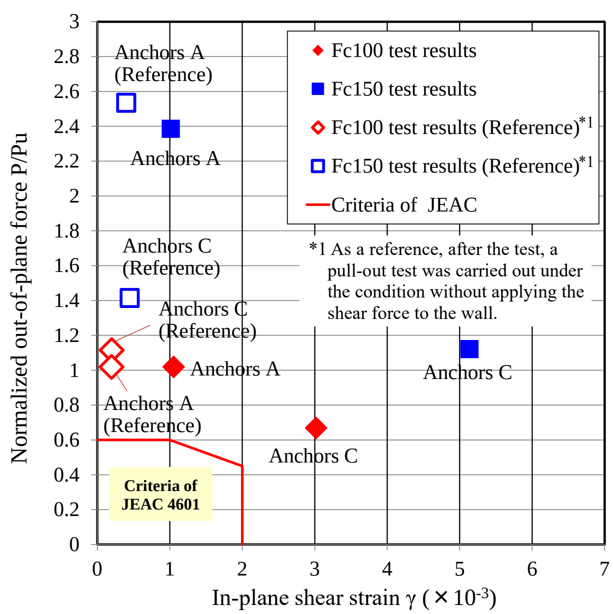


Figure 10. Relationship between in-plane shear strain and the normalized out-of-plane force

Summary of the Test of Shear Wall Embedded Anchorage

The anchorage part embedded in the UHPC greatly exceeded the criteria of the in-plane shear strain and the normalized out-of-plane force prescribed by JEAC. In addition, it was confirmed that the anchor strength was improved by the effect of the steel fiber.

STUDY OF DESIGN METHOD

Based on the test results, design method of anchorage embedded in UHPC was proposed referring to JEAC.

Review of the Current Design Method

Figure 11 shows the reviewable parameters of the current design method based on the test results of the basic characteristics tests of embedded anchorage.

As the result of basic characteristics tests of embedded anchorage, the pull-out strength of the anchorage of UHPC was greater than that of JEAC design formula, and it was confirmed that the pull-out strength of the anchorage of UHPC could be evaluated on the safe side. In addition, as shown in Figure 11, from the test results of the Fc 150 (containing steel fiber) test specimen, the effect of steel fiber was expected to improve the pull-out strength by about 1.4 ~ 1.8 times at a steel fiber mixing ratio of 1%. Therefore, it is considered that the effect of steel fiber can be reflected in the design formula by organizing the relationship between the steel fiber mixing factor *αs* and the steel fiber mixing ratio *p* (%). In addition, by organizing the relationship between the mixing ratio of steel fiber and the pull-out strength taking into account the variation of strength, the design method considering the effect of steel fiber can be established.

Study of the Criteria for In-plane Strain and Out-of-plane Tensile Force

Figure 12 shows the proposed criteria based on the results of shear wall embedded anchorage test.

As shown in Figure 12, it was confirmed that the Fc 100 test specimen (red diamond marker) exceeded the JEAC criteria. It was confirmed that the Fc 150 (containing steel fiber) test specimen had the pull-out strength (*P/Pu* = 1.0) of the JEAC criteria due to the effect of the steel fiber even in the case of receiving the shear strain (about 5000 μ).

From the above results, it was confirmed that the criteria of current in-plane shear strain and the normalized out-of-plane force could be evaluated by JEAC even in UHPC, and the criteria could be extended considering the effect of steel fiber.

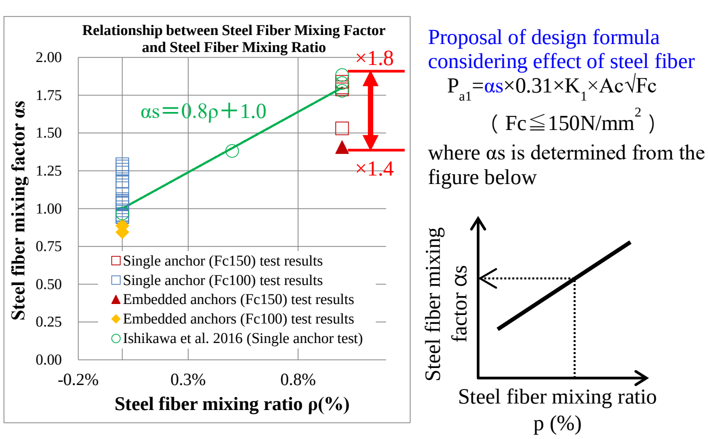


Figure 11. Proposal of anchor design method considering steel fiber mixing factor

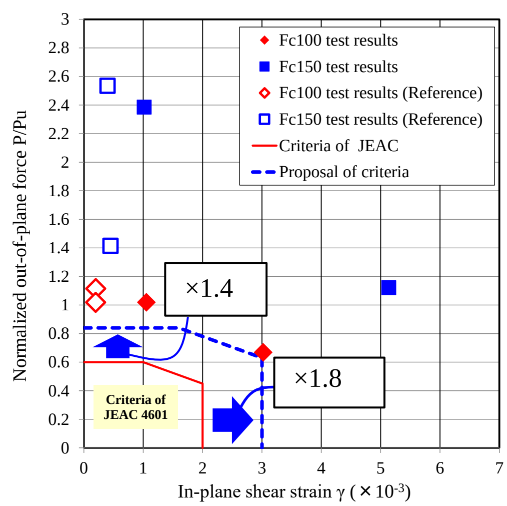


Figure 12. Proposal of criteria based on the test results

Based on the results of basic characteristics tests of embedded anchorage, it is considered that the normalized out-of-plane force can be extended by 1.4 times due to the effect of steel fiber (mixing ratio 1%). Based on the results of shear wall tests (Takeuchi et al. 2019) and the results of the test of shear wall embedded anchorage, it is considered that the shear strain for functional maintenance can be extended from 2000 μ to 3000 μ although there are assumptions in the wall shear test.

Future Issues

Though there is a knowledge that the pull-out strength increases by mixing steel fiber in UHPC, the data to validate it is insufficient. Therefore, in order to propose a design method and to expand the criteria, it is necessary to quantify the dispersion of test results and the relation with the mixing quantity of steel fiber by accumulating test data. In addition, in order to expand the criteria, it is also necessary to obtain data on aging of drying shrinkage and concrete properties.

CONCLUSION

In this study, basic characteristics tests of anchorage part using UHPC were conducted. As a result, it was confirmed that the pull-out strength of anchorage using UHPC is 1.4 times greater than that of normal concrete due to the effect of steel fiber. Also, the anchorage part embedded in the UHPC greatly exceeded the criteria of the in-plane shear strain and the normalized out-of-plane force prescribed by JEAC. Therefore, the strength of anchorage part using UHPC can be evaluated by using the design formula of JEAC on the safe side. By accumulating test data in the future, the criteria may be expanded, and rational design may be possible.

ACKNOWLEDGEMENT

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